Molecular Gas in the Galactic Halo and Beyond

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Abstract. I review recent observations of molecular gas in the halo of the Milky Way and in the Magellanic Clouds. Far-ultraviolet absorption line studies of molecular hydrogen (H_2) with ORFEUS and FUSE have unveiled the presence of a diffuse molecular hydrogen component in intermediate- and high-velocity clouds in the Galactic halo. Although the number of measurements is still quite small, the data suggests that diffuse H_2 in the halo exists only in clouds that contain a sufficient amount of heavy elements and dust, on whose surface the H_2 formation proceeds most efficiently. The implications of these observations for our understanding of the Milky Way halo are discussed.

1 Introduction

Studies of interstellar molecules in the Milky Way and other galaxies are often limited to observations of carbon monoxide (CO) and more complex molecules, that are easily observable by radio emission lines. The most abundant molecule in the Universe, H_2, is difficult to measure directly because of its homeopolarity. Diffuse H_2 ($\log N < 21$) can be studied by FUV absorption spectroscopy of the H_2 electronic transitions in the Lyman- and Werner bands toward stars and extragalactic sources, but those measurements (at low redshifts) require satellites in space. The short-lived *Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer* (ORFEUS; [2]) was the first instrument that allowed a search for H_2 absorption outside the disk of the Milky Way. Today, the more sensitive *Far Ultraviolet Spectroscopic Explorer* (FUSE; [14]) provides a large data base to study H_2 in environments that are different from that found in the local Galactic ISM.

2 H_2 Absorption in the Galactic Halo

2.1 ORFEUS and FUSE measurements

With ORFEUS and FUSE, molecular hydrogen has recently been found in intermediate- and high-velocity H I clouds (IVCs and HVCs, respectively; see B.P. Wakker, this conference) in the Galactic halo at $z > 0.5$ kpc, representing a diffuse molecular gas phase above the Galactic plane that was previously undetected in CO emission or absorption [20] [1].

Table 1. Detections of H_2 absorption in IVCs and HVCs

Target	Cloud Name	$v_{\rm LSR}$ [km s^{-1}]	log $N(H_2)$ [N in cm^{-2}]	log f^a	Instr. + Ref.
		Intermediate-Velocity Clouds			
HD 93521	IV Arch	-60	14.60 ± 0.35	-4.8	O^b, [7]
PG 1351+640	IV Arch (IV 16)	-50	16.43 ± 0.31^c	-3.3^c	F^b
PG 1259+593	IV Arch	-55	$14.10^{+0.21}_{-0.44}{}^c$	-5.4^c	F
PG 0804+761	LLIV Arch	-55	14.71 ± 0.30	-4.5	F, [11]
PG 0832+675	LLIV Arch	-50	16.10 ± 0.32^c	-3.6^c	F
Sk -68 82	IVC toward LMC	$+60$	$15.65^{+0.32}_{-0.19}$	-2.2	O [4]
Sk -60 80	IVC toward LMC	$+60$	present^d	...^{d}	F
HD 100340	IV Spur	-30	present^d	...^{d}	F
Mrk 509	Complex gp	$+60$	present^d	...^{d}	F
		High-Velocity Clouds			
Sk -68 82	HVC toward LMC	$+130$	$15.56^{+0.10}_{-0.06}$	-3.2	O(+F), [10]
NGC 3783	Mag. Stream (LA)	$+240$	16.80 ± 0.10	-2.9	F, [16]
Fairall 9	Mag. Stream	$+190$	$16.40^{+0.26}_{-0.53}{}^c$	-3.7^c	F

^{a} $f = [2N(H_2)/[N(\text{H I})+2N(H_2)]$

^{b} O=ORFEUS; F=FUSE

^{c} Preliminary results

^{d} H_2 is detected, but no column density has been derived yet

The first detection was that of Richter et al. [10], who found H_2 in a HVC in front of the LMC with ORFEUS. Other detections of H_2 with ORFEUS and FUSE in various IVCs and HVCs have followed since then [7] [16] [11]. FUSE observations of extragalactic background sources, and stars in the Magellanic Clouds and in the Milky Way halo provide a large data base to explore the molecular content in IVCs and HVCs over the next years. So far, only a small portion of the data has been analyzed yet. Table 1 summarizes the recent H_2 detections with ORFEUS and FUSE in IVCs and HVCs. I have included new (preliminary) results from on-going investigations of atomic and molecular abundances in the Milky Way halo. As an example, FUSE absorption line data for Fairall 9, PG 1259+593 & PG 1351+640 are presented in Fig. 1. H_2 in the Galactic halo is clearly detected in the Intermediate Velocity Arch (IV Arch) towards PG 1351+640 & PG 1259+593 at approximately -50 km s^{-1}, and in the Magellanic Stream towards Fairall 9 at $+190$ km s^{-1} (for preliminary column densities see Table 1). In contrast, no H_2 is found in the HVC Complex C toward PG 1259+593, although the H I column density in Complex C is relatively high in this direction (log N(H I)=19.92).

2.2 Molecular Fractions and Metallicity

The presence of molecular material in Galactic halo clouds is somewhat suprising, given the expected highly diffuse and low-density nature of these clouds. H I column densities of these clouds are all below 10^{20} cm^{-2}, as derived by

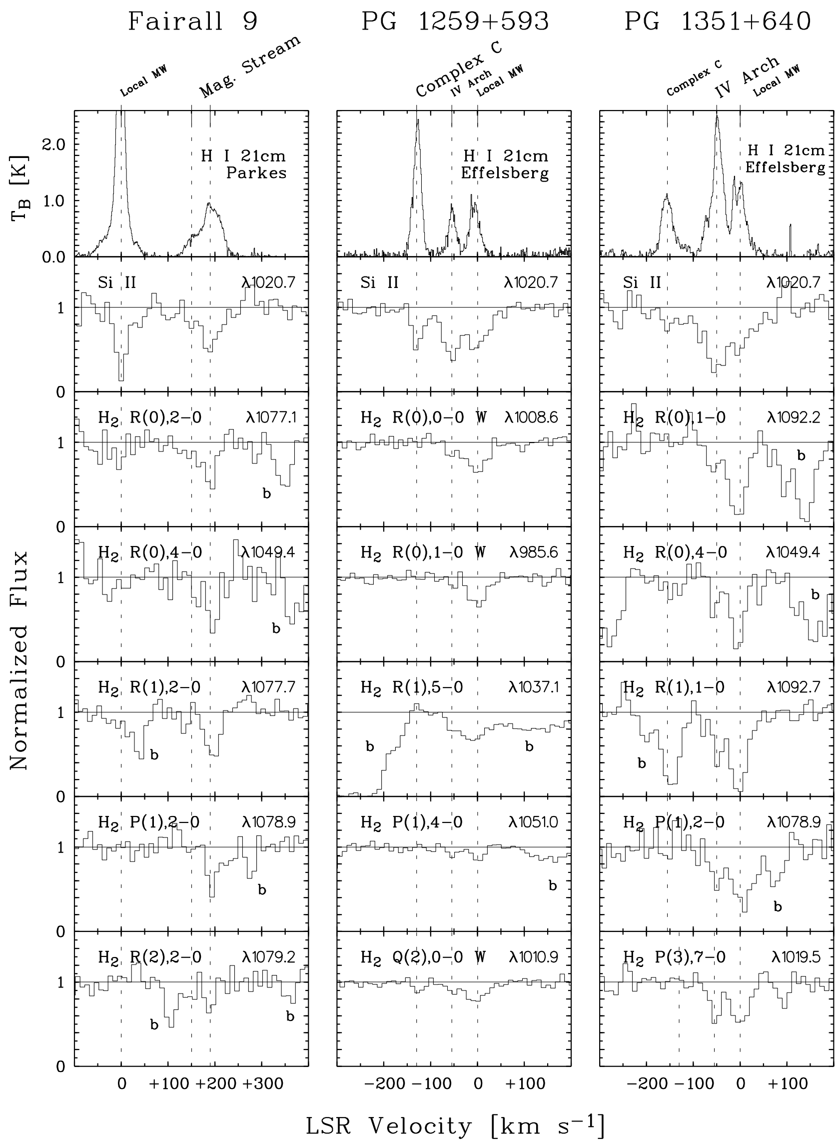

Figure 1: FUSE data of Fairall 9, PG 1259+593 and PG 1351+640 is presented, unveiling the presence of H_2 absorption in intermediate- and high-velocity gas in the Milky Way halo. Velocity profiles of H I 21cm emission from Effelsberg and Parkes data are plotted together with Si II and H_2 absorption for each individual sight line. Toward Fairall 9, H_2 absorption at high velocities is present in the Magellanic Stream at +190 $\mathrm{km\,s^{-1}}$ (left panel). In contrast, no H_2 absorption is seen in Complex C toward PG 1259+593 at −130 $\mathrm{km\,s^{-1}}$ (middle panel). H_2 absorption at intermediate velocities is seen in the IV Arch toward PG 1259+593 at −55 $\mathrm{km\,s^{-1}}$ (middle panel), and toward PG 1351+640 near −50 $\mathrm{km\,s^{-1}}$ (right panel). Blending lines from other species are marked with ‘b’.

H I 21cm data [21], giving no evidence for the existence of dense clumps along the sight-lines where H_2 is found, but beam-smearing effects must be considered carefully. H_2 column densities vary between $\sim 10^{17}$ and $\sim 10^{14}$ cm^{-2}, the latter roughly being the detection limit for H_2 absorption line studies with FUSE. Therefore, the fraction of hydrogen in molecular form $f = [2N(\mathrm{H_2})/[N(\mathrm{H\,I}){+}2N(\mathrm{H_2})]$ is found to be generally low in IVCs and HVCs (see Table 1).

H_2 formation proceeds most efficent on the surface of dust grains, where the H_2 can release part of its binding energy of 4.5 eV. If dust is not available, H_2 can form in the gas phase, but this process is very slow [3]. The relation between dust abundance (as measured by the colour excess $E(B-V)$) and the H_2 column density is well established in the Milky Way [15]. In low-metallicity environments, such as the Magellanic Clouds, the fractional abundance of molecular hydrogen is lower due to the smaller dust-to-gas ratio in the Clouds [13] [19] (see also section 3). Interestingly, the Galactic halo clouds follow a similar trend: H_2 in the Milky Way halo is found mainly in gas that has nearly solar abundances (i.e., IVCs; see Table 1 and Fig. 1), except for the Magellanic Stream, where H_2 is found in two of two observed sightlines at ~ 0.3 solar metallicity [16]. At the lower end of the metallicity scale in Galactic halo clouds, no molecular hydrogen is found in Complex C (e.g., toward PG1259+593; see Fig. 1) at ~ 0.1 solar metallicity along several sight lines, although the H I column densities are in most cases significantly higher than in IVCs, in which H_2 *is* detected. The non-detection of H_2 in Complex C therefore implies that this metal-poor HVC does not contain significant amounts of dust. This is in agreement with the lack of substantial depletion of Fe and Si in Complex C [12].

2.3 H_2 Fomation and Dissociation in the Milky Way Halo

Sembach et al. [16] suggested that the molecular hydrogen found in the Magellanic Stream survived the tidal stripping from the Small Magellanic Cloud, and thus was brought into the Milky Way halo from outside. With respect to other halo clouds containing H_2, however, the formation of molecular gas *within* the halo appears to be as likely. If, for example, IVCs represent the cooled backflow of a Galactic fountain [17], the H_2 found in IVCs must have formed in situ.

In a steady state, the H_2 grain formation and photo-dissociation are equilibriated (see Spitzer [18], page 125). As preliminary calculations show, it is very difficult to describe the observations of H_2 in Galactic halo clouds in an H_2 formation-dissociation equlibrium model. On the one hand, the relatively low H I column densities found in the Galactic halo clouds ($\log N < 20$) require that the H_2 resides in very small (< 0.1 pc) clumps that would have a relatively low sky-covering factor. On the other hand, H_2 in IVCs seems to be surprisingly widespread, requiring at large number of such clumps in the lower Galactic halo. Another possibilty, however, is that the observed H_2 is *not*

in formation-dissociation equilibrium, but represents molecular gas that has formed in dense, compact clouds, but then was dispersed into larger volume, e.g., by diffusion. If so, the low-density H_2 gas is being photo-dissociated on a time scale of $t_{\mathrm{diss.}} = (\langle k \rangle \beta_{0,\mathrm{halo}})^{-1} \approx 10^4$ years. [1] This time-scale is remarkibly short; possibly, Galactic halo clouds are constantly forming and dispersing diffuse molecular cloud cores, preventing the formation of CO bearing clouds and star formation. If some of those clumps can survive, however, they might form a population of young metal-rich halo stars. Interestingly, such stars are indeed observed [5].

3 H_2 in the Magellanic Clouds

With ORFEUS and FUSE, it is now possible to study molecular hydrogen also beyond the Milky Way and its halo, e.g. in the Magellanic Clouds. Richter [13] concluded from ORFEUS data that the molecular hydrogen fraction in the Clouds is reduced compared to the Milky Way due to the lower dust content and the higher UV radiation field. This idea is supported by the more extensive and more accurate FUSE data [19]. Upcoming FUSE observations of Magellanic Cloud stars that have high extinction will help to understand the transition from the diffuse into the dense molecular gas phase in low metallicity environments.

4 Molecular Clumps in the Halo as Dark Matter Candiates

It has been proposed that extremely dense molecular 'clumpuscules' in the outer Galaxy and/or in the Galactic halo might serve as reservoir of cold baryonic dark matter in spiral galaxies [9] . From the presence of the diffuse extreme γ-ray (> 100 MeV) emission from the Milky Way halo (as measured by EGRET; see Kalberla et al. [8]) have proposed that the observed γ-ray flux is caused by interaction between cosmic rays and dense molecular gas clumps by the π_0-decay. These clumps could also account for the extreme scattering events (ESE) that are found toward quasars [6]. No *direct* observational evidence for such a extremely compact molecular gas phase in the halo has been found so far, but UV absorption line studies of extragalactic background sources with FUSE and other instruments will be used to search for evidence of such clumps, which would manifest themselves by partly or fully absorbing the UV continuum from an extragalactic source, if they coincidentally move into the line of sight.

[1] $\langle k \rangle = 0.11$ denotes the possibility that an H_2 molecule is dissociated after photo-absorption; we assume that the photo-absorption rate in the halo is roughly $1-10$ percent of that in the Milky Way disk, thus $\beta_{0,\mathrm{halo}} \approx 0.5 - 5.0 \times 10^{-11}$ s^{-1}.

5 Concluding Remarks

FUV absorption spectroscopy with FUSE and ORFEUS has unveiled the presence of a diffuse molecular hydrogen component in the cores of Galactic halo clouds. Further absorption line studies are necessary to understand the nature of this gas. H_2 absorption spectroscopy of halo clouds might serve as a powerful diagnostic tool to study the physical conditions in the Milky Way halo and might help to obtain new insights on the formation and dissociation of H_2 under conditions that are different from those in the Galactic disk.

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